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The trade-offs between milk production and soil organic carbon storage in dairy systems under different management and environmental factors

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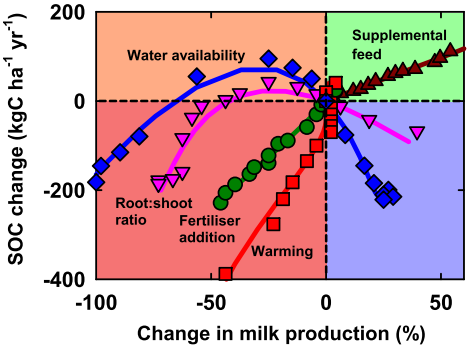
HIGHLIGHTS

- We modelled the response of soil C and milk production to various drivers.
- The model was tested against eddy-covariance data with excellent agreement.
- Outcomes depended on C gain, grazing loss, soil C stability and decomposition rates.
- There were trade-offs between C use for grazing and SOC formation.
- Increasing soil C is difficult because both soil C and milk production need C.

GRAPHICAL ABSTRACT



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ABSTRACT

A possible agricultural climate change mitigation option is to increase the amount of soil organic carbon (SOC). Conversely, some factors might lead to inadvertent losses of SOC. Here, we explore the effect of various management options and environmental changes on SOC storage and milk production of dairy pastures in New Zealand. We used CenW 4.1, a process-based ecophysiological model, to run a range of scenarios to assess the effects of changes in management options, plant properties and environmental factors on SOC and milk production. We tested the model by using 2 years of observations of the exchanges of water and CO_2 measured with an eddy covariance system on a dairy farm in New Zealand's Waikato region. We obtained excellent agreement between the model and observations, especially for evapotranspiration and net photosynthesis.

For the scenario analysis, we found that SOC could be increased through supplying supplemental feed, increasing fertiliser application, or increasing water availability through irrigation on very dry sites, but SOC decreased again for larger increases in water availability. Soil warming strongly reduced SOC. For other changes in key properties, such as changes in soil water-holding capacity and plant root:shoot ratios, SOC changes were often negatively correlated with changes in milk production.

The work showed that changes in SOC were determined by the complex interplay between (1) changes in net primary production; (2) the carbon fraction taken off-site through grazing; (3) carbon allocation within the system between labile and stabilised SOC; and (4) changes in SOC decomposition rates. There is a particularly important trade-off between carbon either being removed by grazing or remaining on site and available for SOC

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formation. Changes in SOC cannot be fully understood unless all four factors are considered together in an overall assessment.

1. Introduction

Cattle-based dairy farming is New Zealand's largest export-earning primary-industry sector (DairyNZ, 2014) as price trends over recent decades made dairying generally more profitable than sheep and beef farming or commercial forestry. There are now almost 5 million dairy cows in New Zealand, grazing on approximately 1.7 Mha of mainly flat, high-quality land. Yields have increased steadily, with average farms now producing about 1000 kg of milksolids (fat and protein) per hectare per year (kgMS ha^{-1} yr^{-1}).

However, dairy farming is also the biggest contributor to New Zealand's net greenhouse gas emissions, primarily due to emissions of nitrous oxide and methane (Kirschbaum et al., 2012; MfE, 2014). Concern also relates to potential losses of soil organic carbon (SOC), and Schipper et al. (2007) analysed archived soil samples and reported a significant SOC loss of 21 ± 18 (95% confidence intervals) tC ha^{-1} to 1 m depth from flat dairy pastures in New Zealand over the preceding 2–3 decades. At the same time, limited sampling of grazed pastures in hill country indicates that they may have gained similar amounts of SOC as those lost on flat dairy land (Schipper et al., 2010).

In a further, more refined analysis, Schipper et al. (2014) found that significant SOC losses on flat land were confined to gley and allophanic soils, with no significant differences between dairy and drystock. These findings, however, conflict with those of the study by Parfitt et al. (2014), who analysed data from a soil-quality sampling programme (Sparling et al., 2004). Sampling depth in that study extended to only 10 cm and data had not been collected for recording changes in SOC and covered a more recent period of observations. In contrast to the SOC losses observed by Schipper et al. (2014), Parfitt et al. (2014) observed no significant change in SOC under flat dairy or drystock pastures.

To date, no readily apparent, and well-substantiated, causes for either of those patterns, or the differences between the studies, have been identified. In principle, the differences between the data sets could relate to differences in sampling methodologies, or they could indicate that the downward trend observed by Schipper et al. (2014) based on sampling over an earlier period has ceased, or even been reversed, over more recent years.

In any case, both New Zealand studies and an earlier European study (Bellamy et al., 2005) indicate that SOC is not inherently constant, but can be changed through changes in pasture management or environmental factors. Environmental conditions are changing globally, with rising temperatures and CO^2 concentrations (Hartmann et al., 2013). Various empirical approaches have shown that temperature is a key determinant of SOC turn-over (e.g. Kirschbaum, 2000) that has led to concerns about SOC losses with ongoing temperature increases that could become a positive feedback to force further climate change (e.g. Sitch et al., 2008). Conversely, increasing CO^2 concentration has been shown to increase plant growth (e.g. Ainsworth and Long, 2005; Hickler et al., 2015; Kirschbaum and Lambie, 2015), which is likely to bring more carbon (C) into any system, with possible positive effects on productivity and SOC.

Dairy-farming has also been using increasing amounts of fertilisers (Parfitt et al., 2012), leading to higher pasture productivity and, together with inclusion of increasing amounts of supplemental feed, have allowed higher stocking rates (MacLeod and Moller, 2006; DairyNZ, 2014). Higher nitrogen inputs, however, have led to increasing nitrate leaching into water ways, which is a serious environmental side effect of dairy farming (Saggar et al., 2008; Ausseil et al., 2013). Supplemental cattle feed may come from hay or maize silage grown by farmers themselves, or purchased from specialist producers. In 2014, New Zealand also imported about 2 Mt of palm kernel expeller (or extract; PKE), a by-product of the palm-oil industry in Indonesia and Malaysia.

Increasing areas of pasture are also being irrigated, especially on the drier east coasts of New Zealand's main islands. The greatest expansion of dairying over recent years has occurred in Canterbury on the east coast of the South Island (e.g. Dymond et al., 2013). There is evidence that irrigation may have reduced SOC (Schipper et al., 2013; Condron et al., 2014; Mudge et al., 2016) even though in natural grasslands, SOC stocks tend to increase with precipitation (e.g. Harradine and Jenny, 1958).

There is interest in understanding how any of these external factors may change SOC (e.g. Parsons et al., 2013; Rumpel et al., 2015), and whether management can be purposefully modified to increase SOC and thereby assist in the task of reducing net C emissions to the atmosphere (e.g. Smith et al., 2008). However, while it is generally desirable to increase SOC levels, dairy farms are commercial enterprises, where milk production is the primary focus and profitability a key determinant of management decisions. The challenge lies in understanding the complex array of interacting factors that together determine SOC levels (Fig. 1). External drivers may change:

1) Net C inputs for SOC formation, principally through net primary production (NPP), which may be supplemented through imported feed;
2) The fraction of C inputs that is grazed or harvested and taken off site versus the fraction retained on site and available for SOC formation. Carbon taken off site includes animal respiration, methane emissions and produce export. Produce export also affects nitrogen stocks with indirect effects on subsequent carbon inputs;
3) The fraction of C allocated to labile versus more resistant pools. Root-deposited C, in particular, is more readily incorporated into stable SOC than surface-deposited C that is more easily respired;

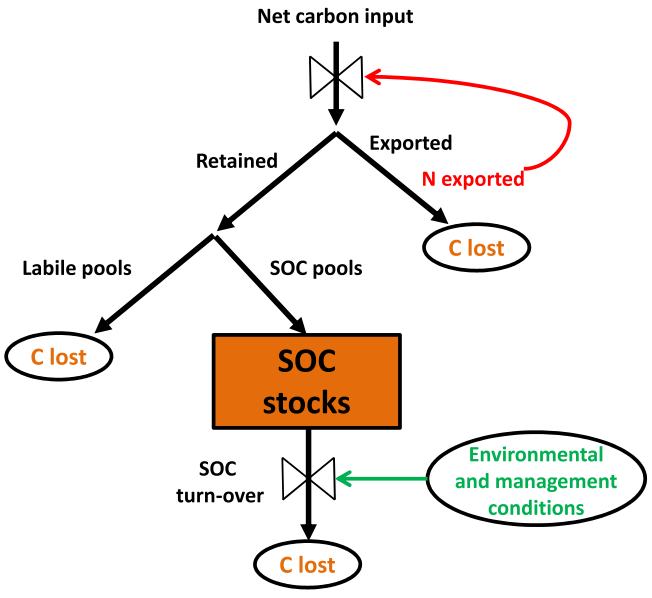

Fig. 1. Interactions between different processes in grazing systems that together determine their soil C stocks. Net carbon input consists of net primary production (NPP) plus supplemental feed.

4) The biophysical drivers of the rate of SOC decomposition that determine the rate of SOC loss from the soil.

In the present work, we used the process-based ecophysiological model CenW 4.1 to explore the effects of different farm management options and environmental changes on SOC storage and milk production. CenW includes the key controlling factors of the gas exchange of vegetated surfaces and the interactions between them (Kirschbaum, 1999; Kirschbaum and Paul, 2002). The model has been tested and validated with data from an intensively studied dairy farm in New Zealand's Waikato region (Kirschbaum et al., 2015a).

Here, we used the model to study SOC changes in response to changes in key input variables using the Waikato farm as a base condition. We explored a number of scenarios of management and environmental changes to assess their effects on milk production and SOC. To help explain the causes for observed changes, we sometimes also present changes in NPP. Ultimately, we aimed to find practices that either (i) increased SOC while maintaining or increasing milk production; or (ii) increased milk production without reducing SOC. We also studied the effects of unavoidable changes in environmental conditions, such as increasing temperature and CO_2 concentration, on SOC and milk production. A preliminary description of the work presented here was given by Kirschbaum et al. (2015b).

2. Materials and methods

2.1. Modelling details

CenW (**C**arbon, **E**nergy, **N**utrients, **W**ater) is a process-based model, combining the major C, energy, nutrient, and water fluxes in an ecosystem (Kirschbaum, 1999; Kirschbaum et al., 2015a). The model's soil organic matter component is based on the CENTURY model in which organic matter is divided amongst a number of pools with different turn-over times, ranging from months to centuries (Parton et al., 1987). Some key modifications of the model formulation were described by Kirschbaum and Paul (2002). This is combined with detailed representation of plant processes and, for application to grazed pastures, with an animal grazing routine (Kirschbaum et al., 2015a). These fluxes are then combined to simulate the C balance of systems over time. For the present work, we used CenW version 4.1, which is available, together with its source code and a list of relevant equations, from http://www.kirschbaum.id.au/Welcome_Page.htm.

The model runs on a daily time step. Major processes are C assimilation by plants through photosynthesis, and losses through respiration by grazing animals, autotrophic plant respiration and heterotrophic respiration by soil organisms. These fluxes are modified by temperature, and by nutrient and water balances. The model contains a fully integrated nitrogen cycle that allows the testing of the interaction between nutrient gains through fertiliser additions and biological nitrogen fixation by legumes, and nutrient losses from produce removal, leaching and gaseous losses.

Biological nitrogen fixation is assumed to be inversely proportional to a calculated plant nitrogen limitation term. When nitrogen is not limiting, such as with heavy fertiliser additions, simulated biological nitrogen fixation reduces to zero. With lower fertiliser additions, pastures become progressively more nitrogen limited, with biological fixation rates increasing commensurately.

Soil water balances are also modelled in detail as they can constitute an important constraint on productivity. Water balances are affected by soil depth and water-holding capacity down to the depth that can be accessed by plant roots. Effective water-holding capacity is thus determined by the lesser of soil depth and maximal rooting depth, and soil-textural characteristics to that depth. Water can be gained by rainfall or irrigation and lost through evaporation from the soil surface and wet foliage after rainfall, or through plant transpiration. If soil water content exceeds the soil's water-holding capacity (i.e. field capacity), excess water is lost by deep drainage beyond the root zone.

For modelling grazing events, it is assumed that animals consume 55% of foliage (Pal et al., 2012), of which 50% is assumed to be lost by respiration, 5% as methane (Kelliher and Clark, 2012), and 18% removed in milksolids (Crush et al., 1992; Soussana et al., 2010; Zeeman et al., 2010), with the conversion between C and milksolids based on Wells (2001). For modelling SOC changes, it is important to include these C fluxes from the system as any removed C becomes unavailable for SOC formation. Of ingested feed, 27% is assumed to be returned to the paddock as dung or urine.

CenW was parameterised and validated using detailed measurements from an experimental grazed dairy farm in New Zealand's Waikato region (Scott Farm, 37.46°S 175.22°E). The experiment was conducted over 2 years (2008–2009) with continuous measurements of CO_2 and water fluxes with an eddy covariance tower. The paddocks were predominantly covered with perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.), the species that typically dominate New Zealand's pastoral systems. Full details are provided by Mudge et al. (2011), Rutledge et al. (2015), and Kirschbaum et al. (2015a).

2.2. Statistics

The overall goodness of fit of the model was described by calculating model efficiency (*EF*), determined as (Nash and Sutcliffe, 1970):

$$EF = 1 - \frac{\sum (y_o - y_m)^2}{\sum (y_o - \bar{y})^2}$$

where y_o are the individual observations, y_m the corresponding modelled values, and $\bar{y}$ the mean of all observations.

2.3. Scenarios

The simulations used standard management, and the soil and environmental conditions observed at our experimental site in the Waikato region as base conditions (Mudge et al., 2011; Rutledge et al., 2015; Kirschbaum et al., 2015a). We used an 8-year weather sequence that was used repeatedly for longer runs. That approach ensured the capture of inter-annual variability while avoiding any confounding effects through any climate-change signal that might have been present in a longer weather sequence.

Base plant and management conditions are given in Table 1. For the simulations, all parameters were kept constant except those specifically mentioned in respective sections below. Grazing used an automatic routine where pastures were grazed whenever biomass reached a set threshold. This procedure adjusted grazing off-take in line with any changes in pasture productivity.

Table 1
Base conditions for the simulations shown here.

Variable	Base condition
CO_2 concentration	400 μmol mol^{-1}
Mean annual temperature	13.7 °C
Annual precipitation	1214 mm yr^{-1}
Supplemental feed	0 tDM ha^{-1} yr^{-1}
Fertiliser application	200 kgN ha^{-1} yr^{-1}
Grazing threshold	2.8 tDM ha^{-1}
Target root:shoot (high N)	0.75
Target root:shoot (low N)	1.5
Effective soil water-holding capacity (to rooting depth 70 cm)	216 mm

The model was run for 50 years under base conditions to allow all system properties to come to a near-equilibrium state. Conditions were then changed according to specified scenarios as detailed below, and the system was run for a further 50 years under the new conditions. Reported changes in SOC were calculated as the average rates of change over the 50-year simulation period. Other variables were calculated as average rates over the final 8 years of those simulations.

2.3.1. Supplemental feed

In the base case, no supplemental feed was supplied, and the simulations explored the effect of adding different amounts of supplemental feed. It was assumed that the extra feed had an average C concentration of 50% and a C:N ratio of 20 so that adding 1 tDM (500 kgC) also added 25 kgN. The effects of these nutrient additions and nutrient removals in extra grazing were automatically included in the simulations.

2.3.2. Fertiliser addition

The base condition included an annual fertiliser application rate of 200 kgN ha^{-1} yr^{-1}, and we explored the effects of application rates between 0 and 300 kgN ha^{-1} yr^{-1}. Fertiliser was applied in six equal applications, one in early autumn, and five in monthly intervals from late winter to early summer. It was assumed that 20% of applied fertiliser would be lost by ammonia volatilisation (Ledgard et al., 1996; Saggar et al., 2013). The simulations included N fixation by legumes, which decreased as external fertiliser applications were increased (Ledgard et al., 2009). Biological N fixation was not sufficient to match the possible rates of external N applications.

2.3.3. Target root:shoot ratios

Plant biomass allocation was calculated based on the assumption that plants varied their C allocation towards achieving certain target root:shoot ratios (Kirschbaum et al., 2015a). Those target ratios themselves were assumed to be variable, with enhanced root growth under nutrient-limited conditions (e.g. Saggar et al., 1997). Without grazing, modelled plants generally maintained their root:shoot ratios close to set target values. However, grazing removed foliage while leaving root biomass largely undisturbed, thus altering root:shoot ratios to greatly exceed any set target values. Following grazing, new growth was then preferentially allocated to leaf growth until set target root:shoot ratios were reached again.

Under base conditions, root:shoot ratios were set to 0.75 for nutrient-sufficient conditions and 1.5 for notionally extremely nutrient-limited plants (Table 1). This was based on empirical observations of root biomass (Dodd and Mackay, 2011; McNally et al., 2015), chase-labelling experiments (e.g. de Neergaard and Gorissen, 2004; Scott et al., 2012), and the parameter fitting from our experimental site (Kirschbaum et al., 2015a). We then explored the effect of changing non-stressed target ratios over the range from 0.5 to 2, while maintaining the ratio of the stressed and unstressed target ratios to 2. Changing these target ratios corresponded either to changes in species composition towards species that may naturally grow more or less roots, or to changes within the dominant species through plant breeding.

2.3.4. Rooting depth (effective water-holding capacity)

The effect of changing rooting depth was emulated through changing the total effective water-holding capacity of the soil. Under base conditions, based on our experimental observations (Kirschbaum et al., 2015a), plants were assumed to have roots down to 70 cm for a total water-holding capacity of 216 mm. A soil's effective water-holding capacity is determined through the physical properties of each soil layer and by the depth to which plant roots can explore the soil. Thus, different effective water-holding capacities can result either from differences in soil physical properties or from differences in rooting depth. Any water percolating below the defined rooting depth of plants was assumed to become unavailable and would eventually be lost from the system. It was also assumed that different rooting depths resulted from changes in root architecture rather than through changing C allocation to roots.

2.3.5. Water availability (rainfall plus irrigation)

Average annual rainfall under base conditions was 1214 mm yr^{-1} (Table 1), and we explored the effects of halving to doubling that amount. To simulate reduced rainfall, we simply multiplied observed daily rainfall by appropriate fractions to achieve respective annual amounts. To simulate increased rainfall, irrigation water was added at weekly intervals to achieve annual totals.

2.3.6. Temperature change

Temperature affects the rate of SOC decomposition, and it affects plants through direct physiological means and indirectly through the rate of water loss by evapotranspiration (e.g. Kirschbaum, 2004). We used the weather conditions at our experimental site as the base condition and explored the effect of changes in temperature from cooling by 1 °C to warming by 5 °C, applied equally to daily minimum and maximum temperatures. These simulations did not include any possible direct temperature effects on cow metabolism (see Hill and Wall, 2015).

To appropriately include the indirect effects through changed water relations, it was important to carefully consider changes in absolute atmospheric humidity with warming. If absolute humidity had been maintained constant with increasing temperature, it would have greatly increased the vapour pressure deficit of the air, and thereby the rate of water loss, leading to water stress and likely reductions of plant productivity. However, it is more likely that dewpoint temperatures will increase in line with daytime temperatures, leading to increased absolute humidity but maintaining a fairly constant relative humidity (Trenberth et al., 2007). In practice, this was achieved by taking absolute vapour pressures from the observed weather records and calculating dewpoint temperatures that corresponded to observed vapour pressures. Dewpoint temperatures were then changed by the same amount as daytime temperatures, and new absolute vapour pressures were calculated from the adjusted dewpoint temperatures (Kirschbaum, 2004).

2.3.7. Atmospheric CO_2 concentration

The atmospheric CO_2 concentration reached about 400 μmol mol^{-1} by 2015, and is increasing further by about 2 μmol mol^{-1} yr^{-1} (Hartmann et al., 2013). We used 400 μmol mol^{-1} as the base condition and explored the effect of varying CO_2 concentration from 300 to 800 μmol mol^{-1}. This covers the approximate range of CO_2 concentrations from pre-industrial concentrations to those that could be reached by 2100 (van Vuuren et al., 2011).

3. Results and discussion

3.1. Model validation

The model was tested against 1 year of foliar biomass measurements and 2 years of eddy covariance data that were aggregated to daily sums (Fig. 2). Details of the experiment, the parameter fitting, and the challenges of appropriately capturing all C losses during grazing events have been described by Kirschbaum et al. (2015a). Evapotranspiration was modelled extremely well (Fig. 2a), with model efficiency of 0.91 for comparison with daily and 0.96 for weekly-averaged data. The model was thus able to simulate the interaction between seasonal and plant factors in controlling evapotranspiration rates as well as short-term phenomena, such as responses to day-to-day changes in weather patterns.

Photosynthesis was also very well modelled, with model efficiencies of 0.79 and 0.84 for daily and weekly comparisons (Fig. 2b) even though those observations had not even been used for model parameterisation. Daily photosynthesis covered a wide range of values ranging from near zero during a severe drought in the first summer of the observation period, low values of about 25 kgC ha^{-1} d^{-1} in the middle of winter, and

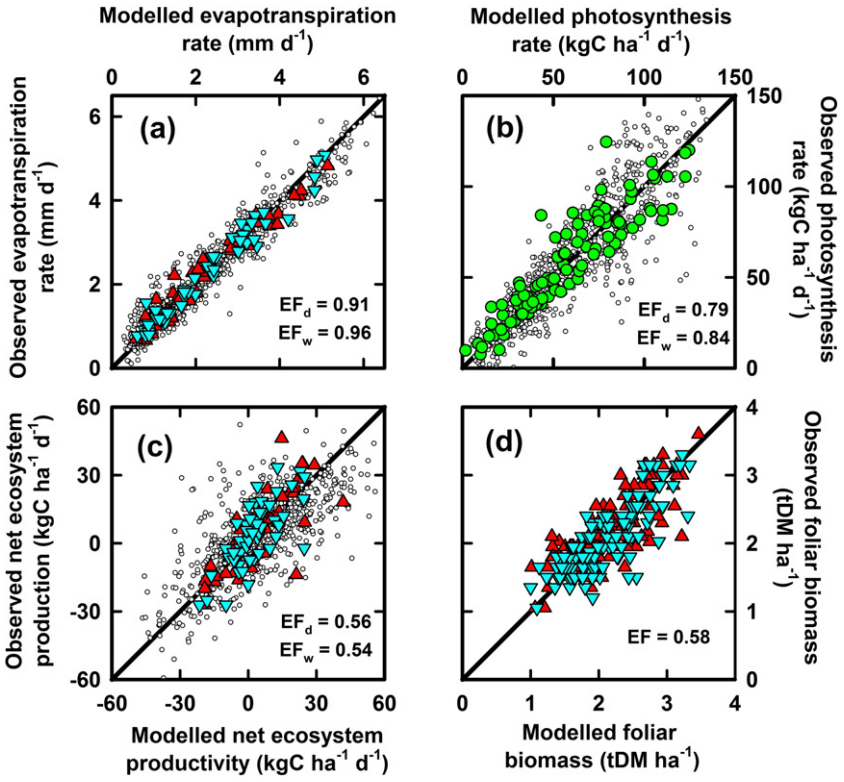

Fig. 2. Observed versus modelled rates of evapotranspiration (a), photosynthesis (b), net ecosystem production (c) and foliar biomass (d). Small symbols in (a) to (c) show daily observations, and larger symbols show weekly averages. Red triangles in (a), (c) and (d) are from a calibration data set and blue triangles are from a validation data set. Photosynthesis was not used for model optimisation, thus requiring no distinction between calibration and validation data sets. Positive values for net ecosystem production indicate net uptake. "EF" refers to model efficiency against the validation data, with subscripts 'd' and 'w' for daily and weekly data. Based on the data of Kirschbaum et al. (2015a).

peaks of up to 125 kgC ha^{-1} d^{-1} during summer periods without water shortages (Kirschbaum et al., 2015a).

Agreement between modelled and observed respiratory C losses was less good. This was largely due to the challenge of capturing highly episodic grazing events that could release C at rates that were an order of magnitude greater than combined plant and heterotrophic soil respiration rates. The challenges inherent in the capture of these events were described and illustrated in detail by Kirschbaum et al. (2015a).

Consequently, the combined C fluxes that constituted net ecosystem production were not modelled as well as photosynthesis alone, but still adequately, with model efficiencies of 0.54 and 0.56 for weekly and daily values, respectively (Fig. 2c). The adequate modelling of C gain and loss with their seasonal dynamics and response to important aspects of pasture management then allowed adequate description (EF = 0.58) of the dynamics of foliar biomass (Fig. 2d). Overall, the comparisons confirmed that CenW is an appropriate tool for describing the key dynamics of grazed pastures and can be applied for scenario analyses.

3.2. Changed driving variables

Having parameterised the model for our experimental site, we then explored the effect of changes in some key driving variables. These are presented and discussed below.

3.2.1. Supplemental feed

Adding supplemental feed increased milk production (Fig. 3a) and SOC (Fig. 3b) across all addition rates. Cattle consumed the supplemental feed and converted 18% of it into milksolids, with no significant feedback processes in the system so that the responses of milk production and changes in SOC were more or less linear.

However, SOC increases were small, with an addition of 6 tDM ha^{-1} yr^{-1} (3 tC ha^{-1} yr^{-1}) needed to raise SOC by just over 120 kgC ha^{-1} yr^{-1}. Hence, only about 4% of added C was sequestered in SOC, while 96% was exported in produce or respired by cattle or soil organisms. Even of the 4% sequestered in SOC, only some was sequestered in resistant pools with long turn-over times. A larger fraction remained in only moderately resistant pools that turned over within the 50-year

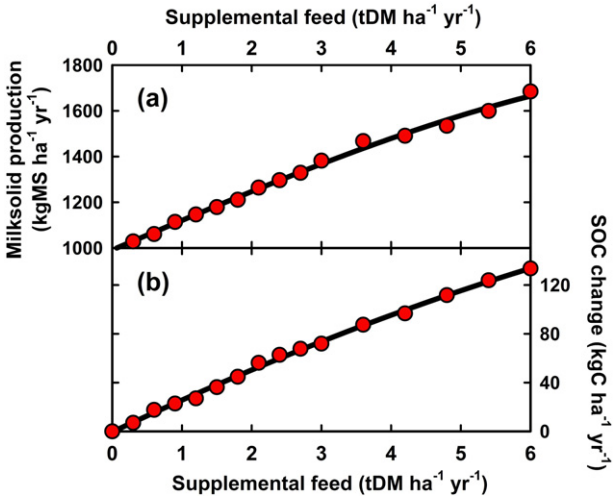

Fig. 3. Modelled milksolid production (a) and soil organic carbon (SOC) changes (b) with different amounts of supplemental feed. Milksolid production is shown as the average over the last 8 years of a 50-year run, and SOC changes are shown as the average change over the 50-year simulation period. Lines in the figure are simple polynomials drawn for the visualisation of trends.

simulation window so that net sequestration rates diminished over time (Fig. 4).

The SOC increase was thus rapid over the initial years, with an application of 6 tDM ha^{-1} yr^{-1} leading to an initial gain of over 0.2 tC ha^{-1} yr^{-1} over the first few years of supplemental feeding (Fig. 4b) for an eventual addition of about 7 tC ha^{-1} after 50 years (Fig. 4a). The additionally sequestered C initially consisted largely of relatively labile material. In subsequent years, new labile C was added with each feed addition, but previously added labile C decomposed and was lost from the system so that the net SOC gain became progressively smaller over time. In the longer term, only a small fraction of more resistant C remained and sustained a smaller longer-term rate of SOC sequestration.

In terms of the underlying processes (Fig. 1), supplemental feed simply added more C to the system, with beneficial effects for both milk production and SOC. The extra feed predominantly benefited milk production as the extra C was first ingested by cattle so that SOC benefited only indirectly through dung addition. Dung deposited on the soil surface was less effective for SOC formation than root deposited material. This positioning of added C therefore contributed to the proportionately large C loss before it could be stabilised in SOC.

Supplemental feed also added nutrients, while export in additional milk production and accelerated N leaching removed nutrients. The simulations here assumed a C:N ratio of 20 in supplemental feed which approximately matched the extra N requirements of an intensified system. For supplemental feed with greater or lesser C:N ratios, the reduced or enhanced relative N availability would provide an important additional aspect to drive the overall system response.

While the simulations suggested that SOC could be increased through adding supplemental feed (Figs 3 and 4), the feasibility of that option is constrained by external considerations, such as the availability of additional land to produce that feed. For an assessment of the overall greenhouse gas impact of adding supplemental feed, it would be necessary to consider the combined impacts on feed-producing and feed-consuming land units together. Cropping generally reduces SOC (e.g. Murty et al., 2002) so that transfer of maize silage between farms, for example, might result in SOC gains on pasture sites but losses from cropping sites, and it would require whole-system approaches to assess impacts on the whole range of inter-linked system components.

3.2.2. Fertiliser addition

The simulations showed that milk production (Fig. 5a) and SOC changes (Fig. 5b) consistently increased with increasing fertiliser application rates. Arrows in the figure show the base case conditions that had been assumed for a standard farm in the Waikato region, and SOC changes are given relative to those base-case conditions. The simulations showed that further fertiliser application rates beyond the base case led to only minor changes in both milk production and SOC, but that both would decrease substantially if fertiliser application rates were reduced.

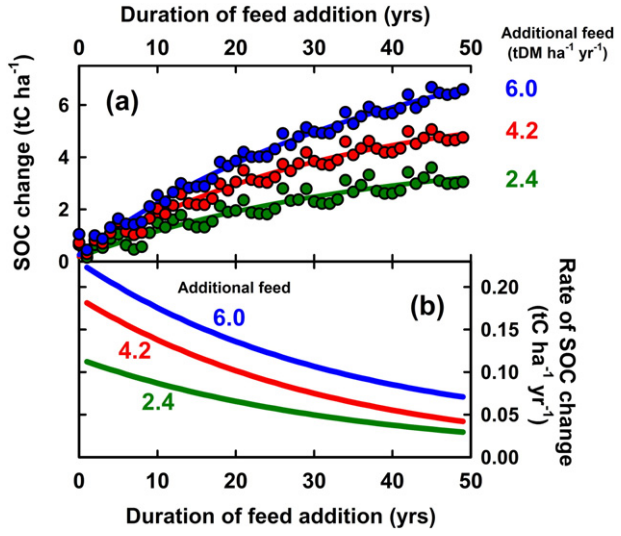

Fig. 4. SOC change (a) and corresponding rates of SOC changes (b) over 50 years of applying additional feed at different annual rates as shown.

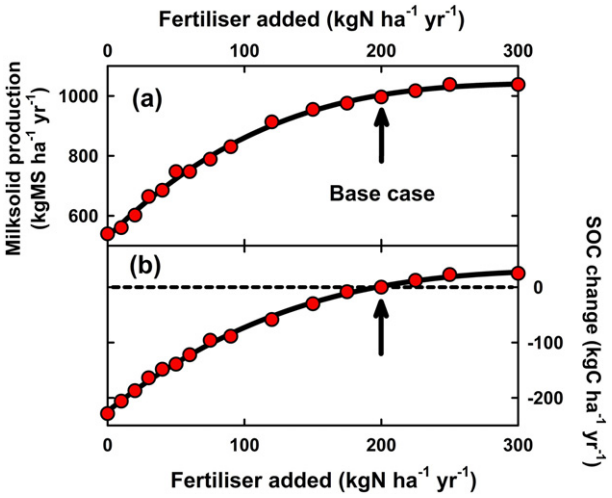

Fig. 5. Modelled milksolid production (a) and SOC changes (b) with different fertiliser addition rates. Other information as for Fig. 3. Arrows indicate the base-case conditions.

Nitrogen exports in milksolids constituted a substantial and ongoing drain of nitrogen from the site (Parsons et al., 2013) which, together with gaseous (Saggar et al., 2008) and leaching losses (Haynes and Williams, 1993), reduced nitrogen resources and subsequent productivity. Such impoverishment could only be prevented through large fertiliser inputs as biological nitrogen fixation was assumed to be insufficient to match the high rate of nutrient removal.

With lower fertiliser inputs, the system degraded and reached a new steady state with lower productivity and lower SOC, estimated as a difference of >200 kgC ha^{-1} yr^{-1} between the highest and lowest fertiliser application rates (Fig. 5b). Similar fertiliser effects on SOC have been observed empirically in crop (Ludwig et al., 2011) and forest systems (Johnson and Curtis, 2001) but have not yet been tested under New Zealand's intensive grazing systems, despite their heavy reliance on application of N fertilisers.

The magnitude of the effect was controlled through the interplay between rates of nitrogen loss through export in produce, leaching and gaseous losses, and nitrogen gains, principally biological nitrogen fixation. Biological nitrogen fixation is highest in nitrogen impoverished systems (e.g. Ledgard et al., 2009), which can partly, but not fully, compensate for differences in fertiliser application rates. Large amounts of nitrogen are removed in animal produce. Grazing leads to further nitrogen losses through leaching from urine spots (Haynes and Williams, 1993), and gaseous losses can be large both from urine spots and from fertiliser when it is applied (Ledgard et al., 1996; Saggar et al., 2008, 2013). These nitrogen losses must either be continuously replenished through fertiliser application plus biological nitrogen fixation, or the system is forced to move to a lower nitrogen and C state, with lower productivity and lower related nitrogen losses (Parsons et al., 2013).

3.2.3. Target root:shoot ratios

The simulations suggested that milk production could be increased considerably through reducing target root:shoot ratios (Fig. 6b), largely driven by a strong effect on total NPP (Fig. 6a). Increasing leaf allocation also meant that C was allocated to the plant organs that were grazed and used for milk production. Pastures with a low root:shoot ratio therefore

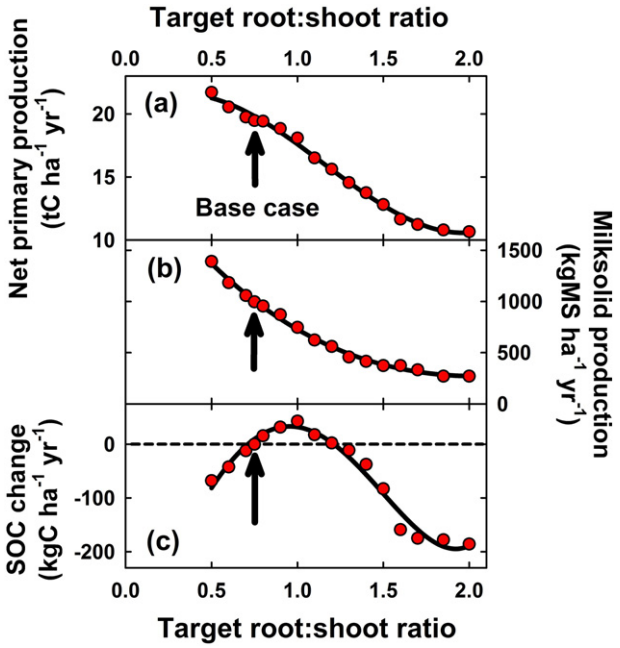

Fig. 6. Modelled NPP (a), milksolid production (b), and SOC changes (c) for different target root:shoot allocation ratios. Other details as described in the legend of Fig. 5.

not only fixed more C than pastures with higher ratios, but proportionately more of that C could be grazed as well.

Associated changes in SOC were fairly small, and maximal at an intermediate target root:shoot ratio (Fig. 6c). At low root:shoot ratios, little C was allocated below ground, with most C grazed and removed offsite, instead. At higher root:shoot ratios, insufficient C was allocated to foliage production to enable maximum light interception so that NPP decreased (Fig. 6a) and reduced the amount of C available for SOC formation, although that was partly compensated by the increasing proportion of C allocated below-ground. With the two key processes changing in opposite directions, the overall change in SOC was relative small across a wide range of target root:shoot ratios (Fig. 6c).

It is important to note that NPP in our modelled system was assumed to be limited by the availability of water and nitrogen, with other nutrients adequately available. Plants need roots to access water and nutrients from the soil, but both water and nitrogen (as NO_3^-) are very mobile in the soil (e.g. Wilkinson and Lowrey, 1973) so that relatively little root mass is needed for their uptake. That means that whole-sward productivity could be maximised with less investment in root growth in surface soils. The pattern depicted here is thus likely to hold only for nitrogen-limited systems but not for systems limited by phosphorus or other poorly mobile soil nutrients. If phosphorus, which is very immobile in the soil (Wilkinson and Lowrey, 1973), is the limiting nutrient, systems may require greater root mass to access available resources adequately in order to achieve maximum productivity.

Optimal root allocation is also constrained by a difference in optimal growth strategies between individual plants and plant swards. Since genetic selection operates via the competition between individual plants, it selects strategies that are optimal for individual plants rather than for swards as a whole (see King, 1993). While whole swards could not increase their access to nitrogen or water through greater root proliferation in surface layers, individual plants could obtain a greater share of available resources through greater root growth, thus forcing individual plants into growth strategies that are not optimal for stands as a whole (King, 1993). The competition between individual plants thus forces them to adopt growth strategies that reduce the productivity of stands as a whole.

It might, therefore, be possible to breed plants to grow in genetically uniform stands where lower root allocation could improve overall pasture and milk production. Similar advances have been achieved in crop breeding where uniform lower-stature plants have allowed substantial yield improvements through maximising harvest indices (e.g. Gale and Youssefian, 1985). In croplands, genetically identical swards can be maintained through annual re-sowing. Pastures, however, are semi-wild populations that are subject to competition within swards and are likely to turn into less productive swards over time as stronger individual plants attain dominance. To retain more productive genetically uniform swards might require frequent pasture renewal.

3.2.4. Rooting depth (effective water-holding capacity)

The effect of changing rooting depth was emulated here through changing the total effective water-holding capacity of the soil. With increasing water-holding capacity, NPP increased up to a water-holding capacity of about 200 mm, with even a slight decrease thereafter (Fig. 7a). The increase from very low (i.e. 50 mm) to moderate (i.e. 150–200 mm) water-holding capacity was related to the ability for ongoing growth and ecosystem function through brief dry periods. With an effective water-holding capacity of 50 mm, it took only a few days of warm weather without rain for the available water to be depleted so that water stress developed and prevented ongoing growth. A greater water-holding capacity prevented development of that stress and allowed ongoing productivity through brief dry spells. The slight reduction of NPP at very high water-holding capacities related to nutrient impoverishment through increasing nutrient loss in produce removal (Fig. 7b).

Increasing water-holding capacity led to an increase in milk production (Fig. 7b) that was proportionally greater than the increase in NPP (Fig. 7a). Increasing water-holding capacity thus also allowed more complete capture of fixed C in grazing off-take. This was particularly apparent at higher water-holding capacities where milk production continued to increase while NPP even decreased slightly with increasing water-holding capacity.

The greater effectiveness of capturing C for milk production came at the expense of reducing the amount of C available for SOC formation, leading to reducing SOC with increasing water-holding capacity (Fig. 7c). Even though NPP increased with increasing water-holding capacity, the extra C was primarily used for milk production. The net effect of slightly increased NPP but a proportionately larger capture in grazing

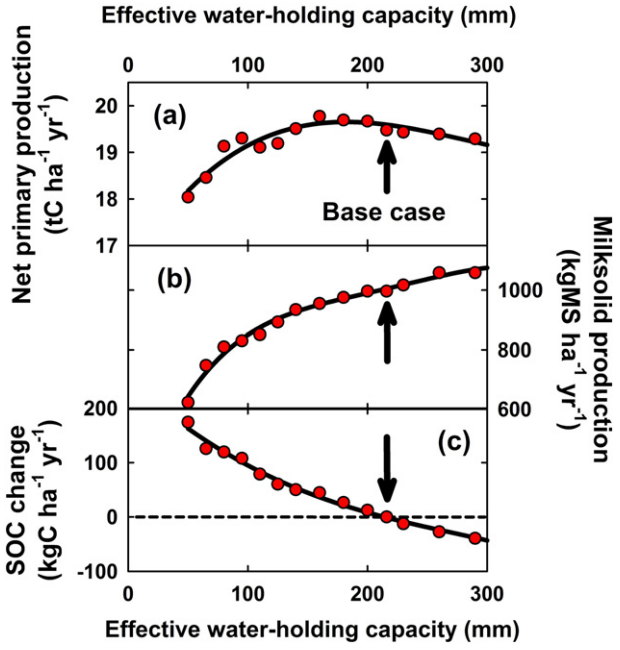

Fig. 7. Modelled NPP (a), milksolid production (b), and SOC changes (c) for different effective soil water-holding capacities. Other details as described in the legend of Fig. 5.

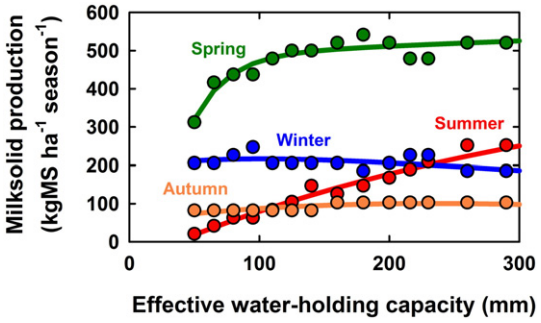

Fig. 8. Seasonal changes in milksolid production with different effective soil water-holding capacities.

off-take even led to a net loss of total C retained in the system. With a low soil water-holding capacity, much of the C fixed over summer and during short dry spells in spring and autumn could not be utilised for grazing because growth ceased before it could be grazed. That C was, however, retained on-site and added to SOC formation. With greater effective water-holding capacity, water stress developed less frequently so that pastures continued to grow until they could be grazed, with both C and nitrogen being removed.

The importance of water-holding capacity on productivity over summer is best illustrated by plotting milk production separately over the four seasons. With increasing water-holding capacity, productivity over the summer months made an increasingly important contribution to annual milk production (Fig. 8). Deeper soils allowed excess moisture from winter to be stored and utilised when other growing conditions, like temperature and solar radiation, became more favourable. Deeper soils also conferred slight benefits in spring and autumn, but marginally reduced production in winter mainly because of nutrient drain from increasing produce removal (Fig. 7b).

3.2.5. Water availability (rainfall plus irrigation)

With water availability (rainfall + irrigation) of <500 mm yr^{-1}, the model predicted no milk production at all (Fig. 9b). Productivity was reduced to such an extent that foliar biomass did not reach the threshold needed for grazing by dairy cows. With increasing water availability, milk production increased sharply to reach maximal values at about 1500 mm yr^{-1} and plateaued with further increases in water availability.

NPP followed a similar pattern (Fig. 9a), but was reduced less sharply at the lowest levels of water availability, with nearly half maximal productivity still possible with 500 mm yr^{-1} (see Hunt et al., 2016). With water availability above 1000 mm yr^{-1}, NPP actually decreased slightly with further increases in water availability due to increased nitrate leaching and growth reductions by more frequent water-logging.

SOC also increased with water availability from the lowest water availability values, but reached a peak at about 750 mm yr^{-1} before falling again with further increases in water availability (Fig. 9c). The initial SOC increase was mainly due to the effect of water availability on NPP. However, NPP peaked at moderate water availability, while milk production continued to increase. This required increased use of available C, thus leaving less C on site for SOC formation. Increasing soil moisture also eliminated moisture limitations on decomposition, especially over the summer months, thus contributing to further C losses. Consequently, the most favourable combination of C inputs and decomposition rate for SOC storage was found at an intermediate level of water availability (Fig. 9c).

The response of SOC to precipitation was thus quite complex. Between water availability of 500–1000 mm yr^{-1}, SOC increased with increasing water availability because of increasing NPP. Increases in water availability beyond about 1000 mm yr^{-1} had little effect on NPP but still increased the fraction of C captured for milk production which

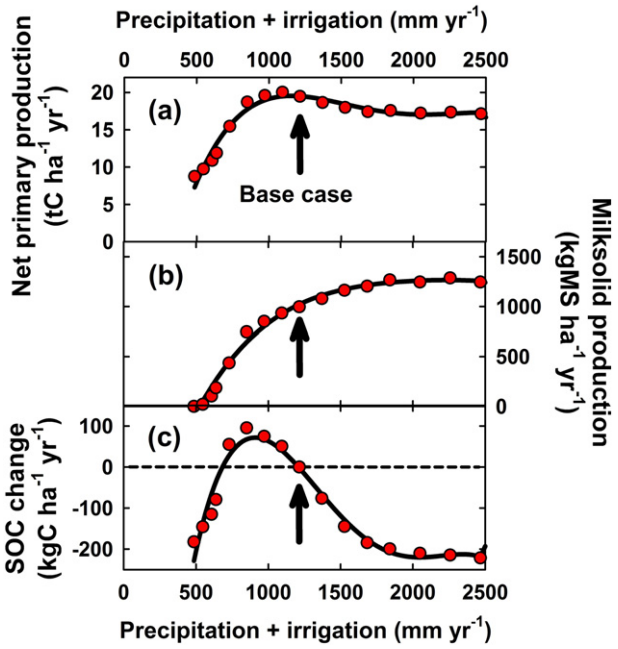

Fig. 9. Modelled NPP (a), milksolid production (b), and SOC changes (c) with different amounts of water availability (rainfall + irrigation). Further details as described in the legend of Fig. 5.

consequently decreased SOC. Increasing water availability also stimulated SOC decomposition by keeping soils wet into the summer months.

This broad picture is consistent with observed increases in SOC when very dry sites are irrigated (Trost et al., 2013) and with New Zealand observations that showed decreased SOC when grazed pastures are irrigated (e.g. Condron et al., 2014; Mudge et al., 2016). It contrasts with observations of unmanaged pasture systems which generally show an increase in SOC with increasing water availability (e.g. Harradine and Jenny, 1958) probably because C removal through grazing plays a lesser role in those systems. It confirms that, for grazed pastures, it is important to not only consider effects on NPP but also the fractional removal of C in animal respiration, methane efflux and produce removal.

3.2.6. Temperature change

In response to changing temperature, NPP was modelled to reach a maximum for warming of about 1.5 °C, but over the range of moderate temperature changes from −1 to +5 °C, changes in NPP were only slight (Fig. 10a). It required even larger temperature increases for more substantial NPP reductions. Warming affected NPP both directly through physiological temperature responses (e.g. Bartholomew and Williams, 2005), and indirectly through increasing rates of evapotranspiration (e.g. Kirschbaum, 2004) that then reduced growth through increasing water stress.

Milksolid production (Fig. 10b) showed a trend similar to that for NPP (Fig. 10a), but with a proportionately greater reduction with increasing temperatures. That was mainly caused by seasonal shifts in milksolid production that reduced the efficiency over the warmer times of the year with which fixed C could be utilised in grazing and milk production (data not shown).

At the same time, while NPP changed only slightly over moderate temperature changes (Fig. 10a), SOC decreased sharply with increasing temperature (Fig. 10c). This was principally due to the stimulation of SOC decomposition rates with increasing temperature (e.g. Kirschbaum, 2000), which increased the rate of C loss from the system. That loss rate was evident over the whole range of temperatures and became strongest for the highest temperatures increases (>4 °C) when lowered productivity added to the adverse effects on SOC dynamics.

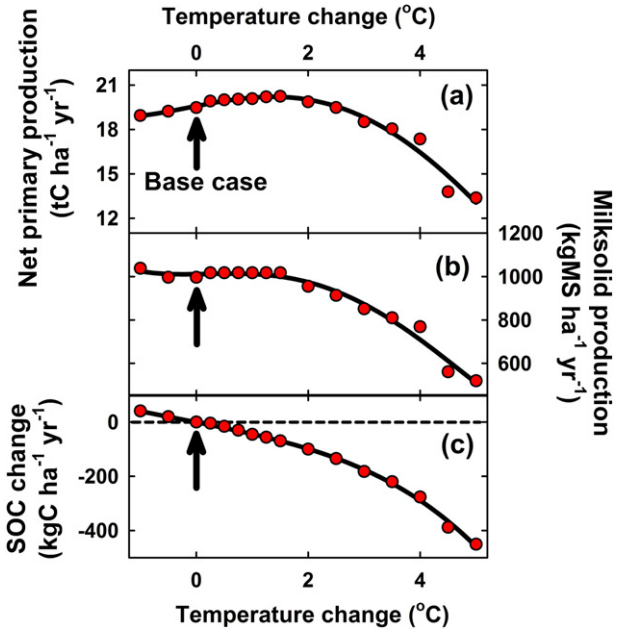

Fig. 10. Modelled NPP (a), milksolid production (b), and SOC changes (c) in response to changing temperature. Other details as described in the legend of Fig. 5.

SOC losses could be substantial and exceed 400 kgC ha^{-1} yr^{-1} in response to the highest temperature increases.

3.2.7. Atmospheric CO_2 concentration

In response to changes in atmospheric CO_2 concentration from a pre-industrial 300 μmol mol^{-1} to a possible late-21st century concentration of 800 μmol mol^{-1} (van Vuuren et al., 2011), NPP was modelled to increase by about 20% (Fig. 11a). The increase was due to increasing photosynthetic rates and improved water-use efficiency, but reduced through adverse fertility changes because of increasing nutrient losses in produce removal (Fig. 11b).

Increased water-use efficiency was particularly important as it extended favourable growing conditions into the summer months and allowed greater capture of fixed C in grazing, thus strongly increasing milk production. However, increased capture of C for milk production left less C on-site and available for SOC formation, which resulted in small changes in SOC by <50 kgC ha^{-1} yr^{-1} over the whole range of conditions (Fig. 11c). The benefit of increasing C inputs was thus completely captured in increased milk production.

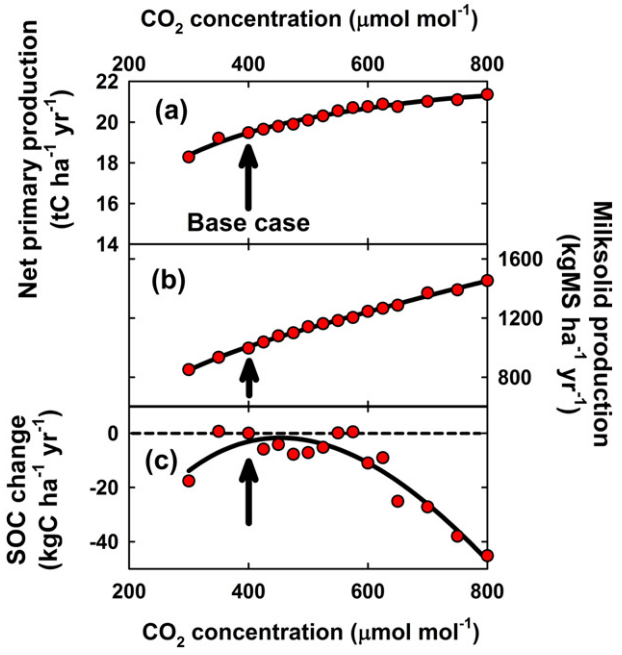

Fig. 11. Modelled NPP (a), milksolid production (b), and SOC changes (c) in response to changing CO_2 concentration. Other details as described in the legend of Fig. 5.

The primary effect of elevated CO_2 was to increase C inputs. Improved water-use efficiency also greatly reduced the impact of drought over the summer months and thereby allowed more complete capture of fixed C in grazing off-take. This left less C available for on-site storage so that SOC barely changed. The connection between C input and ultimate SOC was thus over-ridden by a large change in the proportion of C off-take which was then lost from the system through respiration, methane efflux and produce removal. It highlights how the system's ultimate response to external perturbations was determined by the combined effect of all direct and indirect effects and their interactions.

3.3. Simulation summaries

Fig. 12 summarises the findings of all scenarios by comparing changes in SOC with changes in milk production. Responses to changes in management and plant properties are presented in Fig. 12a and to environmental factors in Fig. 12b. The green sectors describe desirable outcomes, with increases in both SOC and milk production, while the red sectors describe undesirable outcomes with reductions in both. The orange sectors represent increased SOC, but at the expense of reduced milk production, and the blue sectors represent increased milk production at the expense of reduced SOC. The diagram thus focuses on the trade-offs between milk production and SOC formation.

Of the various options, the dual goals of increasing SOC and increasing milk production were achieved only by adding supplemental feed, or by adding even higher amounts of fertiliser than in the base case. They both increased the amount of C gain by the system, either by direct addition in animal feed, or indirectly through improved plant productivity. Constraints on these options are externally imposed. Additional fertiliser additions would further increase the already high environmental problems from nitrate leaching (Ausseil et al., 2013) and ammonia and nitrous oxide emissions (Saggar et al., 2008, 2013). Conversely, reductions in fertiliser use would be desirable for commercial and environmental reasons, but the likely associate reductions in milk production and SOC would need to be factored in to obtain optimal overall outcomes. The use of supplemental feed is constrained through the availability of extra feed, or consideration of the environmental problems associated with its production.

Increasing temperature had strong negative consequences for both SOC and milk production, especially for larger temperature increases. In this case, the dominant underlying factor was the stimulation of SOC decomposition by increasing temperature (Kirschbaum, 2000), with NPP additionally being reduced at the highest temperatures.

For other investigated changes, there were generally trade-offs between changes in SOC and changes in milk production. That trade-off was most clearly seen in response to changes in effective water-holding capacity (due to increased rooting depth). Increased water-holding capacity increased milk production but led to SOC losses mainly because higher water-holding capacity allowed fixed C to be captured more effectively in grazing, with consequent negative effects on SOC. Conversely, milk production decreased with lower water-holding capacity, both because NPP decreased, and because a lower fraction of fixed C was captured in grazer off-take. However, the reduced fraction of C used for grazing left more C available for SOC formation, which consequently increased slightly.

Changing root:shoot ratios and increasing CO_2 concentration resulted in large potential changes in milk production with only minor changes in SOC. For changing CO_2 concentration, SOC remained virtually unchanged as increases in C fixation were largely captured in milk production, with little change in C availability for SOC formation. Responses

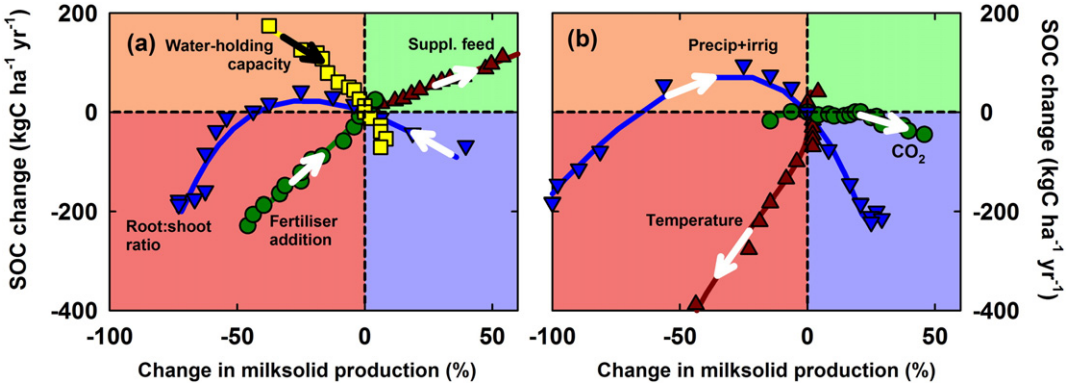

Fig. 12. Trade-off between changes in milk production and SOC for the seven scenarios investigated here. They are displayed in two separate panels here to retain the clarity of the information in each panel, loosely based on management options and plant properties (a) and climate-related changes (b). Different coloured sectors indicate positive or negative outcomes for changes in SOC and milk production. Arrows in the figure show the direction of change for increases in the underlying driving variable.

to changes in target root:shoot ratios were complex. A low root:shoot ratio meant that more C was used for foliage production. That increased overall productivity and the extra C became readily available for grazing. That reduced the fraction of C remaining on site and reduced SOC. Conversely, when more C was allocated to roots, it reduced overall C fixation and the fraction of fixed C taken off-site. The C remaining on site was allocated to roots where senescing roots could most effectively contribute to SOC formation and thus partly negate the effects of reduced C fixation rates.

The most wide-ranging changes were seen for the response to changes in water availability (precipitation + irrigation), with different factors responsible for the modelled changes over the low and high ranges of water availability. At low water availability, the overall response was dominated by changes in C fixation, with changes in both milk production and SOC increasing with changes in water availability. SOC reached a peak at water availability of <1000 mm yr^{-1} when milk production was only 60% of the base-case production rate. For further increases in water availability, milk production continued to increase, but SOC started to decrease because of the increasing proportion of fixed C that was captured in grazing off-take. Over the whole range of water availabilities, a wetter soil also stimulated SOC decomposition to further reduce SOC.

The identified complex interactions also hold lessons for the conduct of future research. To gain better understanding of the impact of different management options and climatic changes on SOC and milk production requires collaboration between field observations and modelling. Field observations provide the relevant observations of the processes that operate in the real world, but field observations are generally restricted to a limited set of locations and conditions, and temporally, to the length of the observation period. Models provide the tools that allow field observations to be scaled up in space and time. They can also more narrowly define and separate out specific factors to be investigated. However, that usually requires model extrapolation outside the range of conditions within which models have been parameterised and tested. Mechanistically-based models, like CenW, allow more confident extrapolation than statistical or purely empirical models, but the validity of any extrapolation remains uncertain even for mechanistically-based models.

The present modelling work can therefore be seen as part of an iterative process. Initial field observations (e.g. Mudge et al., 2011; Rutledge et al., 2014, 2015) provided the observations for model development and testing. In the present work, the model was applied to generate longer-term predictions of changes in milk production and SOC to encapsulate our current understanding of the key interacting system processes. It also provided hypotheses of the interacting components of the system, and these hypotheses provide the basis for future work to refine the model, test specific relationships and, where possible, empirically test the predictions of the model. Over time, that iterative process should lead to improved understanding and better validated models to describe the key processes that operate in grazed pastures in New Zealand.

4. Conclusions

Overall, the simulations presented a diverse picture but they identified few options to usefully increase SOC. In principle, SOC can be changed through changing the amount of C fixed by plants, through the fraction of C lost in respiration, methane efflux and exported in animal produce, through a change in the allocation of C to more or less labile C pools, or through changes in the rate of SOC decomposition. All these could be important and play a greater or lesser role in controlling overall system C balances in response to specific changes. The ultimate effect on modelled SOC storage was determined by the interplay between all of them.

Increasing C inputs (via NPP or supplemental feed) is generally useful, provided that detrimental environmental side effects can be avoided. One may need to employ analyses with wider system boundaries to assess whether beneficial changes on one farm may be negated by detrimental changes elsewhere. Most other changes required trade-offs even within the grazing system itself as both milk production and SOC required C, so C utilisation for one desirable outcome came at the expense of the other.

In the simplest cases, changes in SOC were dominated by changes in C inputs either directly through supplemental feed or indirectly by changing NPP through fertiliser additions. However, fertiliser use in New Zealand is already very high (Parfitt et al., 2012), with significant attendant environmental problems (Ausseil et al., 2013). This leaves little scope to increase SOC through further increases in fertiliser application rates.

Predicted effects on SOC were strongly modulated through changes in the fraction of C lost through grazing, creating a trade-off between C used for milk production and SOC storage. This was strongly expressed in response to changing water-holding capacity, CO_2 concentration and water availability. Within-site allocation patterns also played an important role, especially in response to varying root:shoot ratios. It created a trade-off between C allocation to foliage, which increased NPP and milk production, and allocation to roots, which ultimately contributed to SOC formation. Finally, SOC storage was also very sensitive to SOC decomposition rates, which was most clearly seen in the response to changing temperature.

All these factors are important, and a full understanding of SOC responses to changes in external factors or system properties requires simultaneous consideration of all these directly and indirectly affected mechanisms. Further experimental work is needed to test the veracity of some of the predicted patterns and relationships. Model simulations and experimental work thus need to work in partnership to develop

and test new hypotheses. Modelling work is ultimately needed to generalise experimental observations from specific sites and conditions to wider scales.

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